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FLEXIBLE ELECTRICAL CONDUCTORS FOR HIGH-TEMPERATURE SWITCHGEAR

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Cleveland, Ohio

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16. Abstract

The design, material selection, and mechanical testing of an arch-shaped flexible conductor were covered in this investigation. The conductor was designed for a 600-kVA ac breaker operating at 1000° F (538° C) in a space vacuum. A conductor assembly, with the conductors fabricated from Cube alloy (Cu -0.5 BeO), was successfully tested at 1200° F (648° C) for 1000 hr in a vacuum of 10^{-6} torr (13×10^{-5} N/m^2). During this test, the assembly was mechanically flexed 1000 times, simulating 1000 breaker operations.

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SUMMARY

The design, material selection, and mechanical testing of an arch-shaped flexible conductor were covered in this investigation. The conductor was designed for a 600-kilovolt-ampere ac breaker operating at 1000° F (538° C) in a space vacuum.

A conductor assembly, with the conductors fabricated from Cube alloy (Cu -0.5 BeO), was successfully tested at 1200° F (648° C) for 1000 hours in a vacuum of 10^{-6} torr (13×10^{-5} N/m^2). During this test, the assembly was mechanically flexed 1000 times, simulating 1000 breaker operations.

INTRODUCTION

Conventional electric circuit breakers and contactors are normally operated at ambient temperatures (200° to 300° F or 100° to 150° C), for which the usual current-carrying materials such as oxygen-free high-conductivity (OFHC) copper are adequate. Some future space power systems might require that auxiliary components such as switchgear operate at temperatures near 1000° F (538° C) and in a vacuum for long periods (10 000 hr or more).

An ac breaker and a dc contactor were designed and built to perform in the aforementioned environment (ref. 1). During subsequent testing (10 000-hr endurance), the current-carrying diaphragm in the ac breaker developed some cracks. This diaphragm was made from OFHC copper because it has very high electrical conductivity.

Operation of a breaker or contactor requires that the contacts open a specified minimum distance (0.25 in. or 0.63 cm for the breaker of interest) from the closed position in order to preclude reestablishment of the current flow after arc interruption. The conductor attached to the moving contact should flex with minimum stress, and the material chosen must have sufficient strength to meet the stresses imposed at the elevated temperatures.

To solve this problem of the current-carrying member of the breaker, an investigation was undertaken to develop a flexible electrical conductor for long-term operation. The investigation included the following:

(1) Consideration of an arch-shaped geometry and the stresses involved

(2) Investigation of three candidate materials

  (a) Oxygen-free high-conductivity (OFHC) copper

  (b) Berylco-10 alloy (Cu -2.5 Co- 0.5 Be)

  (c) Cube alloy (Cu -0.5 BeO), in which fine particles of beryllia are dispersed in the copper matrix in order to strengthen the copper and to prevent recrystallization and grain growth (ref. 2)

(3) Environmental testing of arch-shaped conductors using each of the three candidate materials

(4) Environmental testing of the complete current-carrying assembly for the breaker of interest fabricated from Cube alloy and using the arched geometry

CONDUCTOR DESIGN

The ac breaker designed for a large space power system is shown in figure 1. The breaker has a rating of 600 kilovolt-amperes (600 A, 1000 V) at 1000 hertz. The diaphragm conductor indicated in figure 1 was unsatisfactory; it developed cracks. Several conductor geometries that would fit within the envelope of the breaker were considered. An arch-shaped conductor appeared most feasible for the flexible current-carrying member of the breaker. An investigation of this concept included the determination of what materials were available and an analysis of the stresses in the flexing conductors.

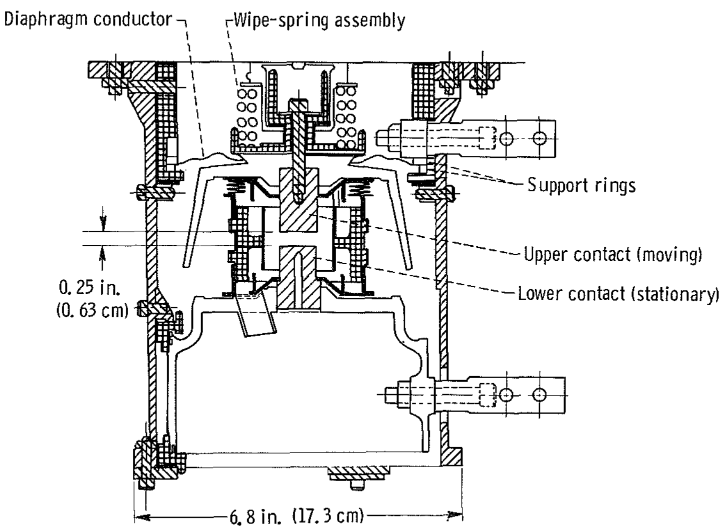

Figure 1. - Alternating-current circuit breaker, rated at 1000 volts, 600 ampers, and 1000 hertz, with diaphragm current-carrying conductor.

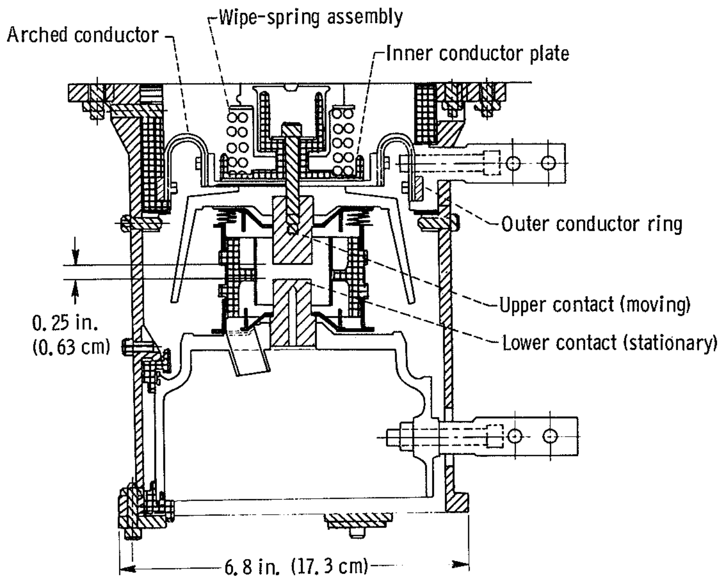

Figure 2. - Alternating-current circuit breaker, rated 1000 volts, 600 amperes, and 1000 hertz, with arch-shaped conductor assembly.

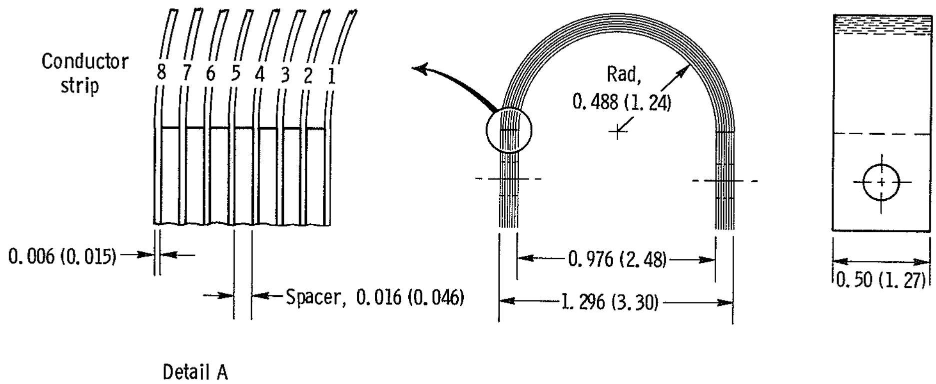

Figure 3. - Arch-shaped conductor. All dimensions are in inches (cm).

Conductor Geometry

The arch-shaped conductor was composed of eight strips 0.50 inch (1.27 cm) wide and 0.006 inch (0.015 cm) thick (shown in figs. 2 and 3). The complete assembly (fig. 4) utilized eight of these arch-shaped conductors.

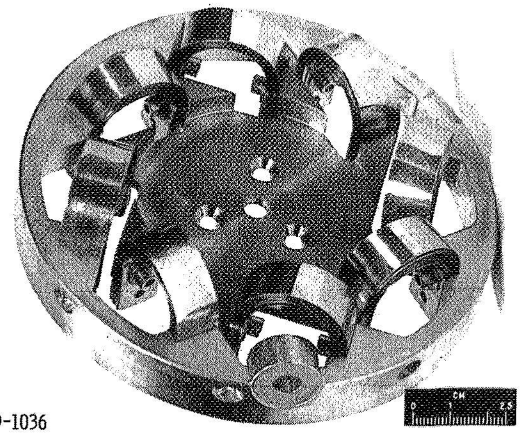

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Figure 4. - Conductor assembly.

TABLE I. - CONDUCTOR PROPERTIES

Material	Reference	Tensile strength at				Electrical conductivity,[a] percent I.A.C.S.
		68° F (20° C)		1000° F (538° C)		
		psi	N/cm^2	psi	N/cm^2	
OFHC Copper	3 and 8	32×10^3	22×10^3	7.0×10^3	4.8×10^3	101
Berylco-10 alloy						
Tempered	4	120×10^3 to 150×10^3	83×10^3 to 104×10^3	(b)	(b)	48 to 52
Annealed	4	35×10^3 to 55×10^3	24×10^3 to 38×10^3	(b)	(b)	25 to 30
Cube alloy	2	80×10^3	55×10^3	45×10^3	31×10^3	85

[a]International annealed copper standard.
[b]Not available.

Conductor Properties

The conductivities and tensile strengths for the three candidate materials (OFHC copper, Berylco-10 alloy, and Cube alloy) are listed in table I.

OFHC copper has the highest conductivity of the three materials but lacks the strength at the required operating temperature. Berylco-10 alloy has the required strength at room temperature but lacks the conductivity. Cube alloy has both the desired properties (i.e., high conductivity and high strength at 1000° F (538° C)).

Current Density

A current flow of 600 amperes through the arch-shaped conductor assembly (fig. 4) results in a current density of 3120 amperes per square inch (483 A/cm^2). This current flow through the diaphragm conductor assembly in the initial testing of the breaker resulted in a temperature rise of 80° F (44° C) (ref. 1).

Stress Analysis

Stresses are analyzed for all eight strips in the arch-shaped conductor. (Sample calculations are presented in the appendix.) The computed stresses ranged from 28 600 to 50 500 psi (19 700 to 34 800 N/cm^2) (see table IV in the appendix).

Material Selection

Cube alloy appeared to be satisfactory for the arch-shaped conductor. Tensile strength data for Berylco-10 alloy at the temperature of interest were not available. As a result, actual testing was required to determine the feasibility of its use in the conductor. The low tensile strength of OFHC copper at 1000° F (538° C) made it an unlikely candidate.

APPARATUS AND PROCEDURE

Test Specimens and Fixtures

Ten arch-shaped conductors of the three candidate materials and one conductor assembly of Cube alloy were fabricated for flexing tests at high temperatures and in a vacuum (see tables II and III). Two test fixtures were also fabricated for these vacuum furnace tests. The 10 arch-shaped conductors are shown in the test fixture in figure 5. The conductor assembly of Cube alloy is shown in figure 4.

The test fixture was constructed to hold the 10 conductors during the 1000-hour high-temperature vacuum test. The fixture allowed a 0.25-inch (0.63-cm) vertical movement of one end of the conductor with the other end fixed. This movement duplicated the contact travel of the breaker of interest. The test fixture was mounted on a tray suspended from the vacuum furnace top flange (fig. 6). A hand-operated mechanical linkage extended through the cover flange of the furnace and was connected to the test fixture for flexural cycling of the conductors.

TABLE II. - CONDUCTOR TEST SCHEDULE

[All tests conducted in vacuum of 10^{-6} torr (13×10^{-5} N/m^2).]

Step	Temperature		Number of 0.25-inch (0.63-cm) flexings	Length of heat soak, hr	Remarks
	°F	°C			
1	500	260	300	0	Inspect visually
2	1000	538	300	0	
3	1050	565	100	100	
4					
5					
6					
7					Remove one-half of conductors for tensile tests and photomicrograph inner arched strips
8	1100	593			Inspect visually
9	1150	621			
10	1200	648			
11	1200	648			
12	1200	648			Remove and inspect remaining conductors for tensile tests and photomicrograph inner arched strips

TABLE III. - CUBE ALLOY CONDUCTOR ASSEMBLY TEST SCHEDULE

[All tests conducted in vacuum of 10^{-6} torr (13×10^{-5} N/m^2).]

Step	Temperature		Number of 0.25-inch (0.63-cm) flexings	Length of heat soak, hr	Remarks
	°F	°C			
1	1200	648	100	100	--------------------------
2					--------------------------
3					--------------------------
4					--------------------------
5					Inspect visually
6					--------------------------
7					--------------------------
8					--------------------------
9					--------------------------
10					Remove and inspect visually

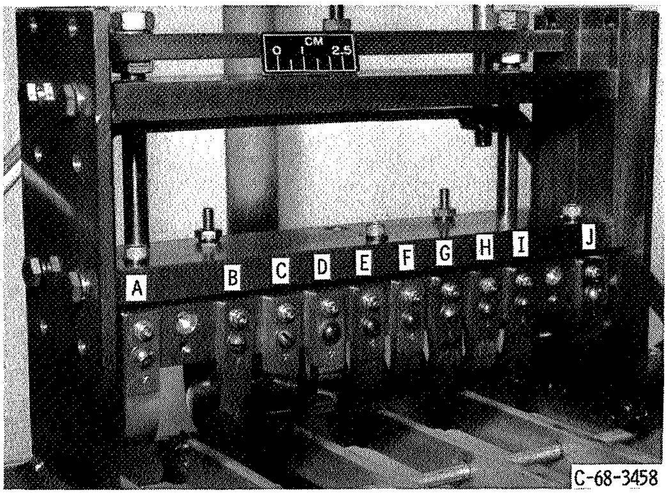


Figure 5. - Test fixture for individual conductors; A and B, 0.005-inch (0.012-cm) OFHC copper; C and D, 0.004-inch (0.010-cm) Cube alloy; E and F, 0.005-inch (0.012-cm) Berylco-10 alloy; G, H, I, and J, 0.006-inch (0.015-cm) Cube alloy.

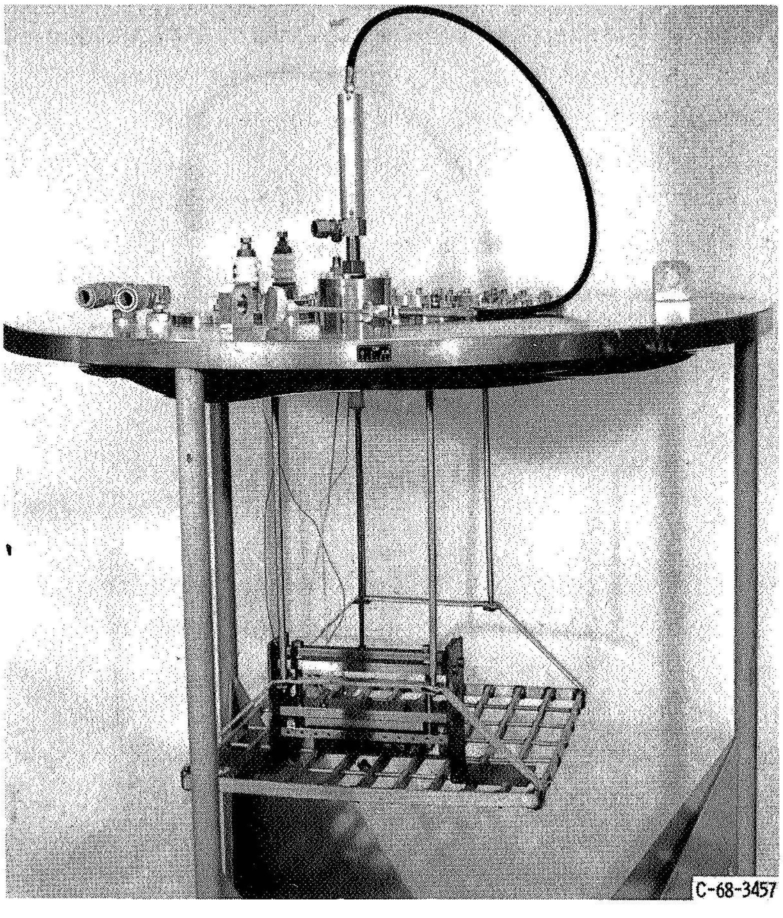


Figure 6. - Conductor test fixture mounted in vacuum furnace cover tray.

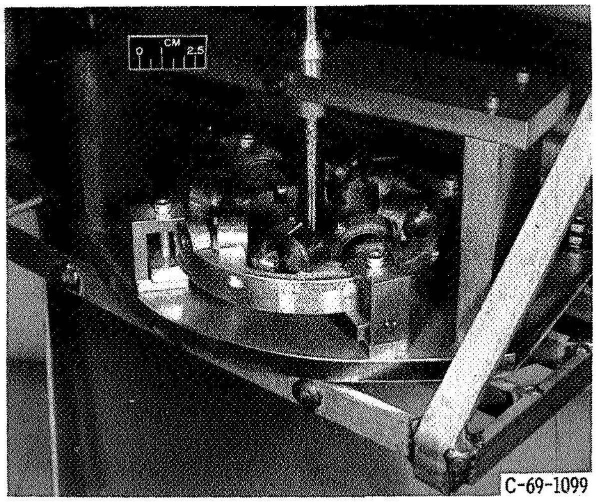


Figure 7. - Conductor assembly and test fixture installed in vacuum furnace mounting tray.

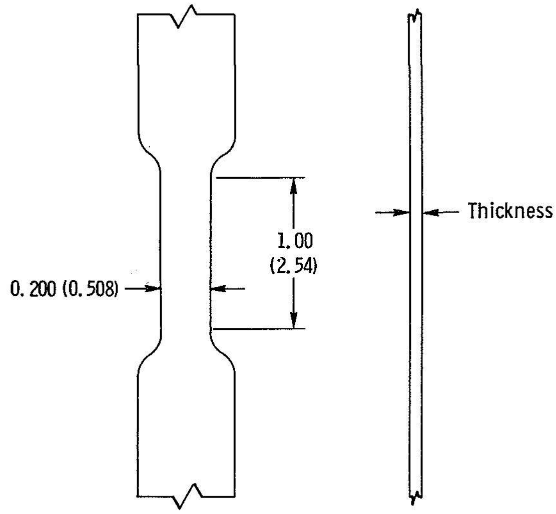


Figure 8. - Tensile strength test specimen dimensions. Thickness varies from 0.004 to 0.006 inch (0.010 to 0.015 cm) for different materials. All dimensions are in inches (cm).

A hand-operated test fixture (fig. 7) was built for the 1000-hour, 1000-flex-cycle, 1200° F (648° C) vacuum test of the Cube alloy conductor assembly (fig. 4 and table III). This assembly is a duplicate of that required for the breaker.

Room-temperature tensile tests were conducted on individual strips removed from the arched conductors. The test strips were milled to a width of 0.200 inch (0.508 cm) for the testing (fig. 8). The cross-sectional area measurement was not as accurate as desired since the thickness was measured to only one significant number. Thus, the values obtained from the tensile tests should be considered only approximate.

The tensile testing was conducted on a 20 000-pound (89 000-N) tensile test machine.

Test Procedure

A test program (table II, steps 1 to 12) was used to examine and compare the 10 conductors of the three different materials during a series of increasingly severe operating conditions. All flexure testing was done in a 10^{-6}-torr (13×10^{-5}-N/m^2) vacuum. Temperatures ranged from 500° F (260° C) at the beginning of the test to a final temperature of 1200° F (648° C). The additional 200° F (93° C) above the normal breaker ambient temperature of 1000° F (538° C) allowed for an I^2R heating effect on the conductors. This temperature rise did not occur since current was not flowing through the conductors during the flexure testing.

Testing was first conducted on the 10 arch-shaped conductors fabricated from the three candidate materials. Prior to heat soak, the conductors were flexed (0.25 in. or 0.63 cm) 300 times at 500° F (260° C) and 300 times at 1000° F (538° C). The conductors were then flexed 100 times at the end of each 100-hour heat soak. This cycle of heat soak and flexing was repeated 10 times for a total of 1000 hours of testing.

After 500 hours of heat soak, five of the conductors (one or more samples of each material) were removed from the test fixture. The inner-arched strips (smallest radii) were removed and milled to the shape shown in figure 8 for room-temperature tensile testing. After 1000 hours of heat soak, the remaining conductors were removed and tested in the manner just described. The smallest-radii strips were tested because the highest stresses occur in these strips. In addition to tensile tests, other inner-arched strips were photomicrographed and examined.

On completion of the conductor testing, the Cube alloy flexible conductor assembly (fig. 4) was tested for 1000 hours (table III, steps 1 to 10). The assembly shown in figure 4 was installed in a test fixture (fig. 7) and tested in a vacuum furnace under 10^{-6} torr (13×10^{-5} N/m^2) at 1200° F (648° C). This assembly was cycled 100 times every 100 hours.

RESULTS AND DISCUSSION

Arch-Shaped Conductor Tests

The flexing tests verified the correlation between the experimental testing and analytical stress calculations of the materials tested. The Cube alloy and Berylco-10 alloy performances were satisfactory. The OFHC copper conductors showed signs of early failure.

Visual (fig. 9) and photomicrographic analyses (figs. 10(e) and (b)) of the conductor

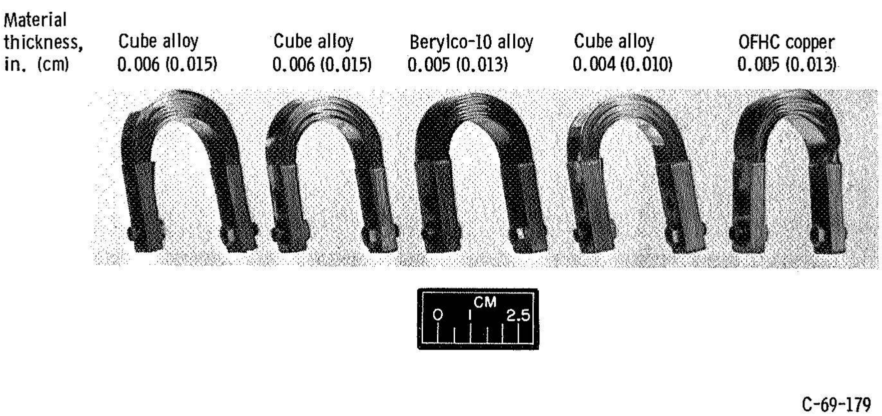
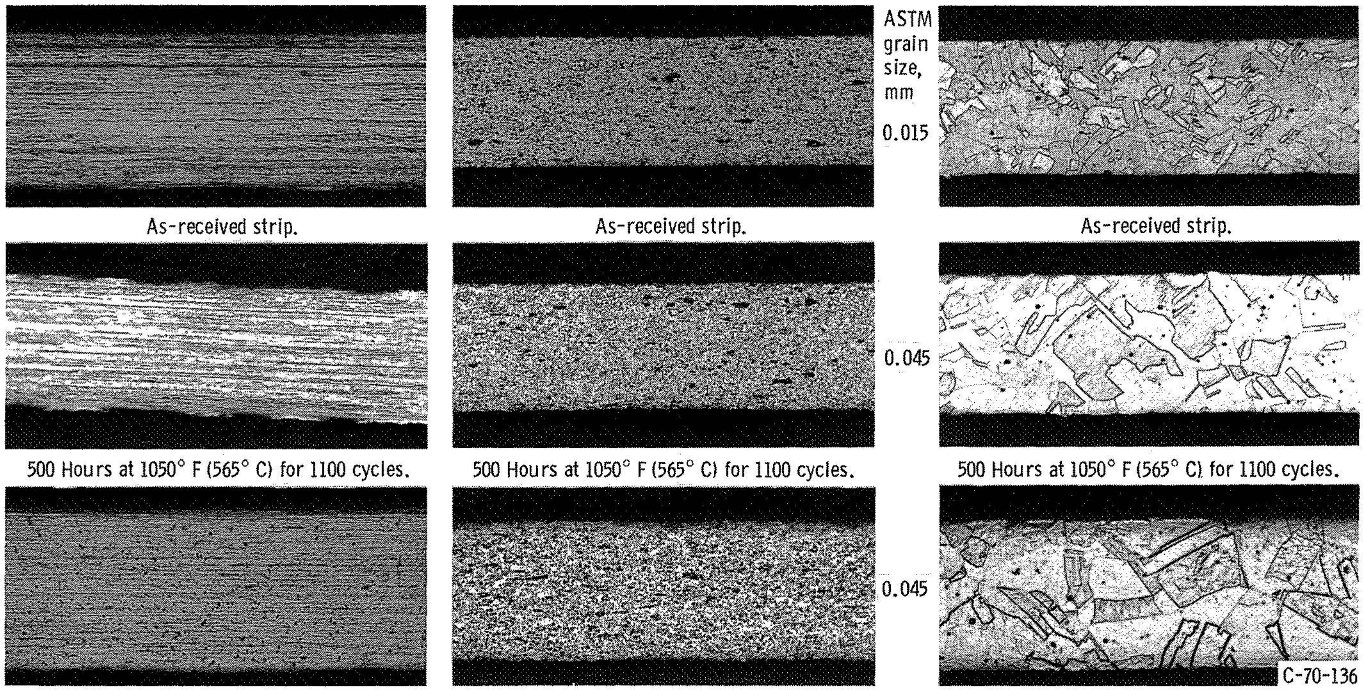


Figure 9. - Conductors after 1000 hours of testing at 1050° to 1200° F (565° to 648° C) and 1600 flexing cycles.



1000 Hours at 1050° to 1200° F (565° to 648° C) for 1600 cycles.

(a) Cube alloy, 0.006 inch (0.015 cm) thick.

(b) Berylco-10 alloy, 0.005 inch (0.012 cm) thick.

(c) OFHC copper, 0.005 inch (0.012 cm) thick.

Figure 10. - Cross-sectional views of conductor strips after flexing tests in vacuum. X250.

strips revealed no change in shape or grain structure after the 1000-hour testing of the Cube alloy and Berylco-10 alloy conductors. There was, however, a slight permanent set in the arched section of both conductors. (The conductors remained in a deflected position at the time of removal from the test fixture.) The conductors had been in a 0.25-inch (0.63-cm) deflected position for the full 1000 hours at 1050° F (565° C) and above (except during the cycling operations). This deflected position is similar to the contact-closed position of the breaker.

Because of the slight setting of the conductors that took place, the working stresses of 28 600 to 50 500 psi (19 700 to 34 800 N/cm^2) for Cube alloy at these operating temperatures are too high and should probably be in the range of 15 000 to 20 000 psi (10 400 to 13 800 N/cm^2).

The OFHC copper conductors were deformed and wrinkled at the end of the 1000-hour testing (fig. 9). However, no actual cracking of the strips had occurred.

Photomicrographs of the OFHC copper conductor strips (fig. 10(c)) showed an increase in grain size from an ASTM specification of 0.015 to 0.045 millimeter after 500 hours but no further increase in grain size at the 1000 hours. This grain growth shows material instability and may be indicative of future failure. OFHC copper is not suitable for operation at 1000° F (538° C) since the tensile strength decreases to 7000 to 8000 psi (4800 to 5500 N/cm^2) at this temperature (ref. 3).

The Berylco-10 alloy conductor performed adequately during the flexure testing. However, it could not be used in the conductor assembly because of its lower electrical conductivity. This lower conductivity would require a larger cross section in the conductor strip and a resultant larger conductor. Thus, the use of Berylco-10 alloy would necessitate design changes in the breaker which would not be necessary because of the acceptable performance of the Cube alloy conductors.

As discussed earlier, the 0.004- and the 0.006-inch (0.010- and 0.015-cm) Cube alloy arched strips performed satisfactorily throughout the testing. The use of the thinner material (0.004 inch or 0.010 cm) in the conductor would require two more conducting strips per conductor, or 16 additional conducting strips in the conductor assembly. However, stresses for the 0.004-inch- (0.010-cm-) thick strips would be 55 percent lower than those for the thicker strips. This, in turn, would reduce the amount of setting that took place. Use of the thinner material is desirable because of the long life (10 000 to 50 000 hr) required. The 0.006-inch- (0.015-cm-) thick material was chosen to increase stiffness, which would reduce vibration problems during launch.

Conductor Assembly Flexing Tests

The conductor assembly had no noticeable deterioration at the end of the 1000 hours

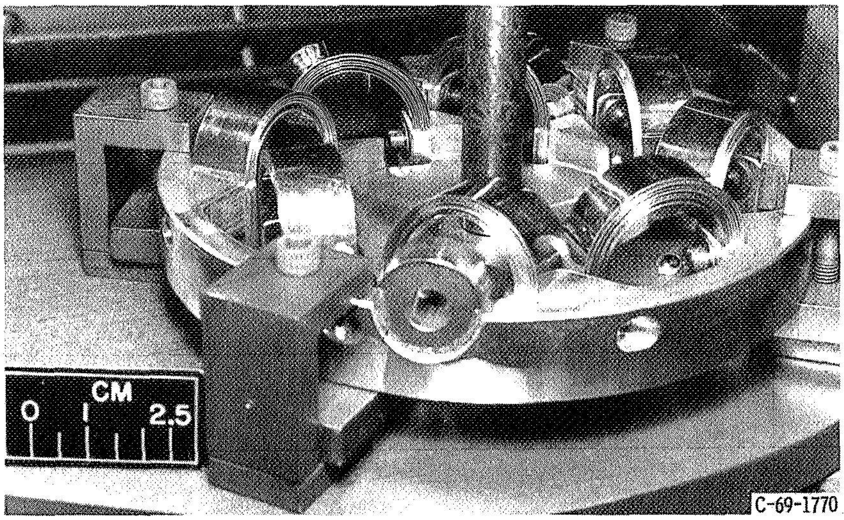


Figure 11. - Conductor assembly after 1000 hours at 1200° F (648° C).

of heat soak in a vacuum at 1200° F (648° C) with 1000 flexing cycles (fig. 11).

The load required to deflect the conductor assembly 0.25 inch (0.63 cm) was calculated to be 6.5 pounds (28.9 N). An actual load of 6.6 pounds (29.3 N) was required to achieve this deflection. This verification shows the agreement between the calculated stresses and those actually involved.

Tensile Testing Results

Tensile test results showed both the Cube alloy strips (0.004 and 0.006 in. or 0.010 and 0.015 cm) to have an ultimate tensile strength (as received) of 82 000 psi (56 000 N/cm^2). This tensile strength value is close to the published value for Cube alloy (ref. 2). The initial tensile strength of Cube alloy dropped 13 percent to 71 500 psi (49 000 N/cm^2) after 500 hours of testing at 1050° F (565° C) and a negligible amount during the second 500 hours of testing at test temperature. Heat-treated Berylco-10 alloy had an initial strength of 131 000 psi (90 000 N/cm^2). This value decreased to 47 000 psi (32 000 N/cm^2) after 500 hours of testing at temperature. This dropoff in strength is mainly due to the annealing of the heat-treated alloy at the 1200° F (648° C) test temperature. This value is in agreement with the published values of annealed Berylco-10 (ref. 4).

OFHC copper tensile strength tests of the as-received strips gave an ultimate strength of 31 000 psi (21 000 N/cm^2). This value agrees with the published value of 32 000 psi (22 000 N/cm^2) for annealed OFHC copper (ref. 3). After 500 hours of test-

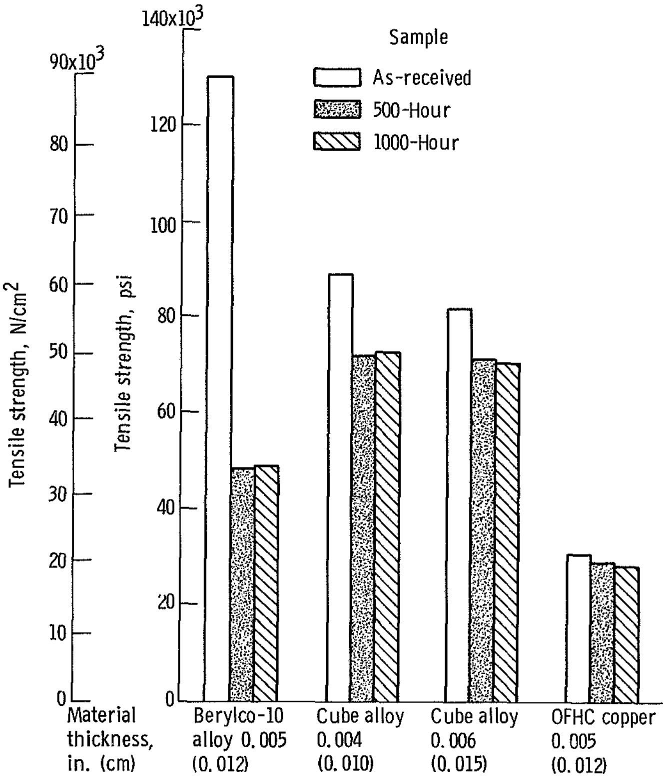


Figure 12. - Room-temperature tensile strength tests of conductor strips.

ing at temperature, the tensile strength dropped to 29 000 psi (20 000 N/cm^2). There was a negligible change in strength between 500 and 1000 hours.

All the room-temperature conductor-strip tensile strength tests (fig. 12) showed a negligible change in strength between the 500- and 1000-hour test samples. The Cube alloy samples (both the 0.004 and 0.006 in. or 0.010 and 0.015 cm) showed only a 13-percent decrease in tensile strength between the as-received and the 500-hour test sample and no decrease between the 500- and 1000-hour tests. Thus, it appears that a 10 000-hour extended life test would result in a minimum decrease in the final strength of the Cube alloy strips used in the conductors.

SUMMARY OF RESULTS

Flexible current conductors were investigated for a 600-kilovolt-ampere circuit breaker to operate in a vacuum of 10^{-6} torr (13×10^{-5} N/m^2) and at a temperature of 1000° F (538° C). The investigation yielded the following results:

1. A conductor assembly containing eight arch-shaped conductors, each made of multiple strips of Cube alloy 0.006 inch (0.015 cm) thick, successfully operated as the current-carrying member of the breaker at 1200° F (648° C) for 1000 hours and for 1000 close-open cycles. A permanent set occurred in the conductors, but it did not affect performance. Because of the slight setting of the conductors that took place, a lower working stress should be used (provided that launch vibration problems would not increase).

2. The major reduction in the ultimate tensile strength of the Cube alloy from the as-received condition took place in the first 500 hours of testing, but the changes during an additional 500 hours were negligible.

3. Berylco-10 alloy would be acceptable as a flexible conductor if size and weight were not important.

4. OFHC copper is unacceptable as a flexible conductor that has to operate in the temperature range 1050° to 1200° F (565° to 648° C).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 15, 1969,
120-27.

APPENDIX - STRESS ANALYSIS OF ARCHED CONDUCTOR STRIP

In the conductor assembly (fig. 4), the outer copper ring is stationary while the inner plate travels downward 0.25 inch (0.63 cm) to close the contacts of the breaker. Since the current-carrying strips are attached to the outer ring and the inner plate by mechanical fasteners, they are flexed each time the breaker closes. This deflection of 0.25 inch (0.63 cm) produces the stresses in the arch-shaped strips.

The stress problem is one of eccentric loading, as indicated in the free-body diagram of figure 13. The force P produced by the solenoid of the mechanism through the

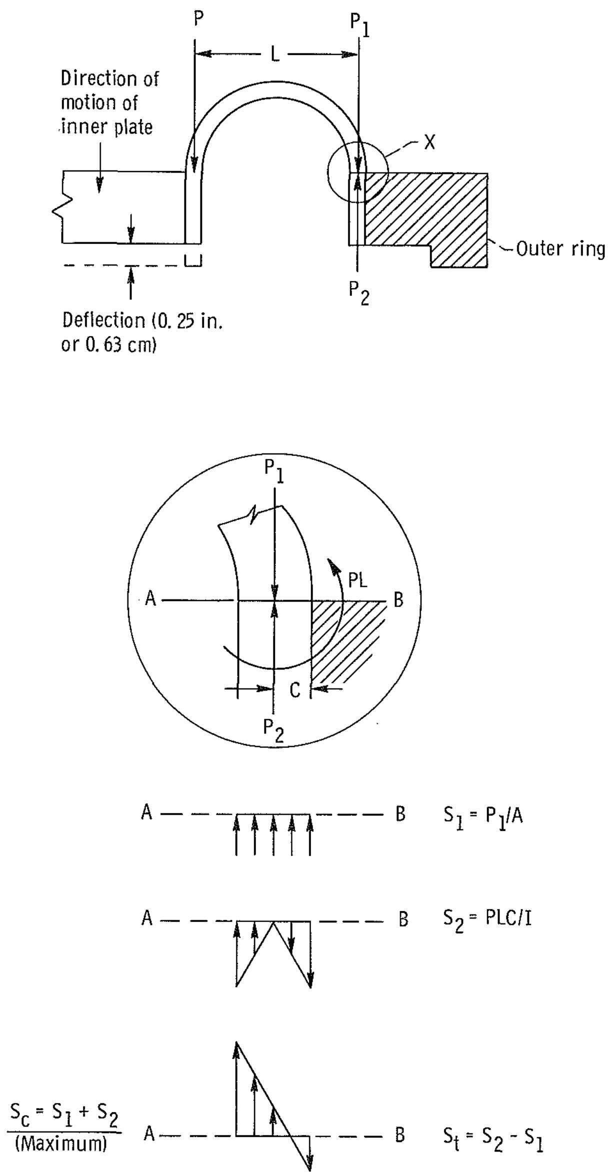


Figure 13. - Free-body diagram.

wipe-spring assembly is at the fastening point of the arched strip and the inner plate. The force is resolved into an axial load P_1 (equal to P) and a couple having a moment PL (or P_2L, since $P_1 = P_2 = P$) (refs. 5 and 6). The axial load P_1 causes a constant unit stress S_1 on the area A of section A-B. Since $P_1 = P$,

$$S_1 = \frac{P}{A}$$

The moment produced by the couple is PL and is resisted by the moment

$$\frac{S_2 I}{C}$$

where

P load

L moment arm length (fig. 13)

I moment of inertia of 0.006-in. (0.015-cm) strip

C one-half of strip thickness

The total effect of the axial force and the couple produces a maximum compressive unit stress S_c

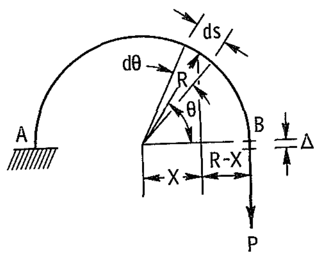
$$S_c = S_1 + S_2 = \frac{P}{A} + \frac{PLC}{I}$$

Since the arched strip is so thin (0.006 in. or 0.015 cm) and its moment of inertia exceedingly small (9.0×10^{-9} in.^{4} or 3.5×10^{-7} cm^4), it can safely be assumed that the unit stress due to the axial force S_1 is extremely small and negligible. (This assumption is verified later in this section.) This leaves only the primary bending stress S_2, due to the moment produced by the couple PL. This stress can be computed by using

$$S = \frac{Mc}{I}$$

Since the load P and, hence, the moment M are not known, it is necessary to express the stress in terms of the deflection, which is known to be 0.25 inch (0.63 cm). The deflection Δ for an arched member fixed at one end is (ref. 7)

$$\Delta = \int_B^A \frac{M^2\,ds}{PEI}$$



Solving this equation for an arched member of 180° and loaded as shown in the sketch results in

$$M = P(R-X) \qquad X = R(\cos\theta) \qquad ds = R\,d\theta$$

$$\Delta = \int_0^{\pi} \frac{P^2(R-X)^2\,ds}{PEI} = \frac{3\pi PR^3}{2\,EI}$$

In terms of the span L ($R = L/2$),

$$\Delta = \frac{3\pi PL^3}{16\,EI}$$

However, since both ends are fixed (fig. 13) (except for the vertical travel requirement of the one end), the load P can be considered to be imposed on two members (ref. 5), which in effect reduces the deflection to one-half. Therefore,

$$\Delta = \left(\frac{1}{2}\right)\frac{3\pi PL^3}{16\,EI}$$

and in terms of the deflection,

$$S_2 = \frac{\Delta 32\ EC}{3\pi L^2}$$

The stress S_2 in arched strip 1 (fig. 3) was calculated to be 50 500 psi (34 800 N/cm^2). Since the stress S_2 is now known, the load P can be determined. For arched strip 1, the load is 0.151 pound (0.67 N). The axial stress S_1 can now be determined. Using the load 0.151 pound (0.67 N), S_1 = 50.3 psi (34 N/cm^2). (As assumed earlier in this section, S_1 is negligible.) The total compressive stress $S_c = S_1 + S_2$ is equal to

$$50.3 + 50\ 500 = 50\ 550.3 \text{ psi } (35\ 000 \text{ N/cm}^2)$$

Table IV lists the stress S_2 and the load P for all eight strips that make up one conductor in the conductor assembly (fig. 4).

The calculated stress for the eight strips ranged from 28 600 to 50 500 psi (19 700 to 34 800 N/cm^2) for a room-temperature condition. At 1000° F (538° C), the actual stresses will be less than those for the room-temperature condition because of the lower value of the modulus of elasticity. Since Cube alloy has a tensile strength of 45 000 psi (31 000 N/cm^2) at 1000° F (538° C), the comparison of values indicates this material to be satisfactory.

TABLE IV. - CALCULATED STRESSES AND

LOADS OF EIGHT CONDUCTOR STRIPS

Conductor strip	Stress, S_2		Load, P	
	psi	N/cm^2	lb	N
1	50.5×10^3	34.8×10^3	0.151	0.67
2	45.2	31.1	.132	.58
3	41.5	28.6	.116	.51
4	38.4	26.4	.103	.46
5	35.5	24.4	.092	.41
6	32.9	22.6	.082	.36
7	30.6	21.0	.073	.32
8	28.6	19.7	.066	.29
Total[a]	--------	--------	0.814	3.60

[a]Total load for eight conductor strips (one conductor); total load of prototype conductor assembly (eight conductors, fig. 4) is equal to 0.814×8 or 6.512 lb (45 N).

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